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THESIS

ATOMIZATION AND COMBUSTION
OF A GELLED, METALLIZED
SLURRY FUEL

by

Bruce Charles Urbon

December, 1992

Thesis Advisor:

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Atomization and Combustion
of a
Gelled, Metallized Slurry Fuel

by

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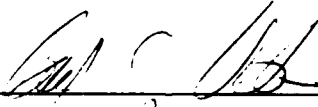
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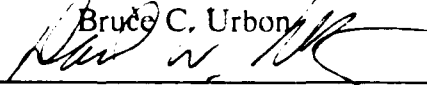
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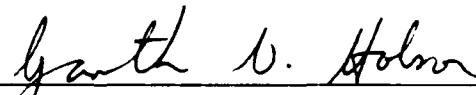


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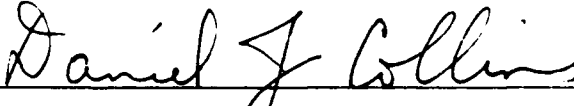
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ABSTRACT

Two commercially available atomizers were tested for their ability to atomize a gelled boron slurry fuel. Particle size distributions were measured in non-reacting flow using a Malvern 2600 HSD Laser Diffraction Particle Sizer. A sub-scale ramjet combustor was designed and fabricated which utilized a sudden expansion inlet dump together with inlet air swirl for flame stabilization. An airblast atomizer produced sufficiently small particles for good combustion, but at the cost of a high pressure drop across the atomizer, making it impractical for use in a slurry fueled ramjet. Sustained steady combustion of the slurry fuel was not achieved using the airblast atomizer. A whistle type ultrasonic atomizer also produced sufficiently small particles and at a much lower pressure drop across the atomizer. Sustained stable combustion was achieved using the ultrasonic atomizer which yielded a combustion efficiency of 76 % at 96 psia and an equivalence ratio of 0.78.

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I. INTRODUCTION

In a volume limited ramjet design a major limitation on performance is the energy available in the fuel. One method for increasing the available energy is to mix a liquid fuel with metal particles. To prevent the metal particles from settling out gelling agents can be added, thus producing a gelled metallized slurry. The problem is that gelled slurries are highly viscous and, therefore, very difficult to atomize into a fine enough spray to take advantage of the high heating value due to the added metal. Poor atomization results in poor combustion efficiency.

A previous investigation conducted by Guglielmi [Ref. 1] characterized the ability of two commercially available airblast atomizers to atomize a gelled metallized slurry fuel. These two atomizers were operated under a variety of flow rates and air-to-fuel ratios and sprayed into the open atmosphere. The conclusion was drawn that the airblast atomizers appeared incapable of providing sufficiently small particles for efficient combustion of a gelled boron slurry using reasonable atomizing air mass flow rates for a ramjet application. Using an airblast atomizer, Guglielmi was able to achieve Sauter mean diameters (D_{32}) as small as 20 microns. These results were achieved using an atomizing air-to-fuel ratio of 14 across a substantial pressure drop.

Poor combustion efficiency using slurry fuel results primarily from the formation of large metal agglomerates that form as the liquid hydrocarbon fuel evaporates from spray particles and burns. The large agglomerates with inherently longer burning times lead to incomplete combustion of the metal particles in the slurry, which causes a loss of combustion efficiency. According to Lipinski acceptable combustion efficiencies could be attained if primary atomization yielded particle sizes of 40 microns with some means of secondary atomization to break up agglomerates formed in the spray. [Ref. 2]

Choudhury [Ref. 3] lists the following four methods to cause agglomerate fragmentation or to prevent agglomerate formation: (1) pulsed irradiation of slurry droplets, (2) internal evaporation in a fuel/water emulsion, (3) explosion of a stable fuel additive, and (4) agglomerate shell fragmentation.

The present study had two major thrusts. The first was to develop a sub-scale ramjet combustor and to use it for evaluating atomizer performance under reacting flow conditions. The second was to test an air whistle ultrasonic atomizer as an alternate means of slurry atomization and to compare ultrasonic atomizer performance with Guglielmi's airblast atomizer results. This part included collecting additional particle size data using the airblast atomizer at air/fuel ratios and pressures reasonable for a ramjet application.

An air whistle ultrasonic atomizer typically requires a much higher air mass flow rate to operate than an airblast atomizer. However, the pressure drop across the ultrasonic nozzle is much lower than that of the airblast atomizer, making the ultrasonic atomizer an acceptable option in a ramjet application. Ultrasonic nozzles are particularly suitable for slurry atomization due to relatively large liquid orifices that make them fairly immune to clogging by highly viscous, particle laden fluids. Furthermore, in a combustion application, the presence of a strong sound field will enhance evaporation and heat release which may improve completeness of combustion, cause better shaped flames, enhance stability and reduce blow-out. [Ref. 4] Ultrasonic nozzles have been successfully used to atomize heavy residual oils providing improved combustion efficiency and a significant reduction in soot [Ref. 5].

II. EXPERIMENTAL APPARATUS AND PROCEDURES

A. APPARATUS

Equipment used for this experiment consisted of a Malvern 2600 HSD Laser Diffraction Particle Sizer, two commercially available atomizers, a sub-scale ramjet combustor, a fuel delivery system and an air delivery and ignition system. The fuel used was a gelled slurry of JP-10/B₄C provided by the Naval Air Warfare Center, Weapons Division, China Lake, CA.

The Malvern 2600 operates on the principle of ensemble light scattering. Particles being sampled scatter light from a low power helium-neon laser. Scattered and unscattered light are then incident on a Fourier Transform lens which forms the far-field diffraction pattern of the scattered light. The far-field diffraction pattern is focused on a series of 31 concentric detector rings. Unscattered light passes out of the optical system through a small aperture in the center of the detector. Measurements can be made regardless of particle velocity or position in the laser beam due to the property of the Fourier Transform lens that the diffraction pattern of a particle is stationary and centered on the optical axis of the lens. During a practical measurement, a large number of particles are present in the laser beam simultaneously. The detector, therefore, senses

the superposition of all the different diffraction patterns generated by the particles. Particle size is determined by the fact that the favored scattering angle of a particle is directly dependent on its diameter. The peak intensity of light scattered by smaller particles will fall on the outer detector rings and vice versa for larger particles. Using a 300 mm range lens, the Malvern 2600 can measure a particle size range from 5.8 to 564 microns.

The first atomizer used, shown in Figure 1, was an airblast atomizing nozzle manufactured by Delavan, Inc. Primary atomization is achieved by introducing air tangentially into the nozzle chamber where there is a region of swirling liquid. Secondary atomization is achieved through impingement of the liquid droplet spray on a deflector ring causing a very fine droplet spray. The second atomizer used, also shown in Figure 1, was an air whistle ultrasonic atomizer manufactured by Sonic Development Corp.. This atomizing nozzle accelerates air through a convergent-divergent nozzle. The supersonic airstream then impinges on a resonator cap creating a strong standing shock wave. The fluid to be atomized is introduced into the airstream near the exit of the divergent section of the nozzle. The fluid is atomized as it passes through the standing shock wave.

Figure 2 is a schematic representation of the fuel delivery system. Nitrogen gas was used to pressurize a tank containing JP-10. The JP-10 passed through a cavitating

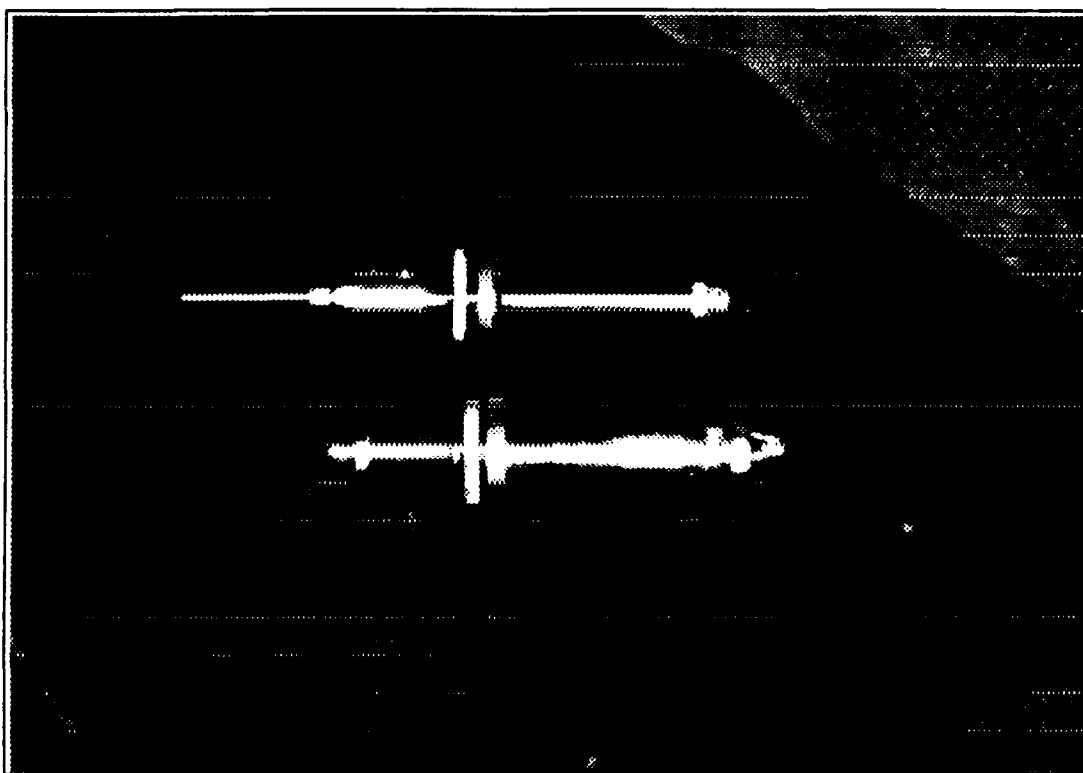


Figure 1: Airblast Atomizer (top) and Ultrasonic Atomizer

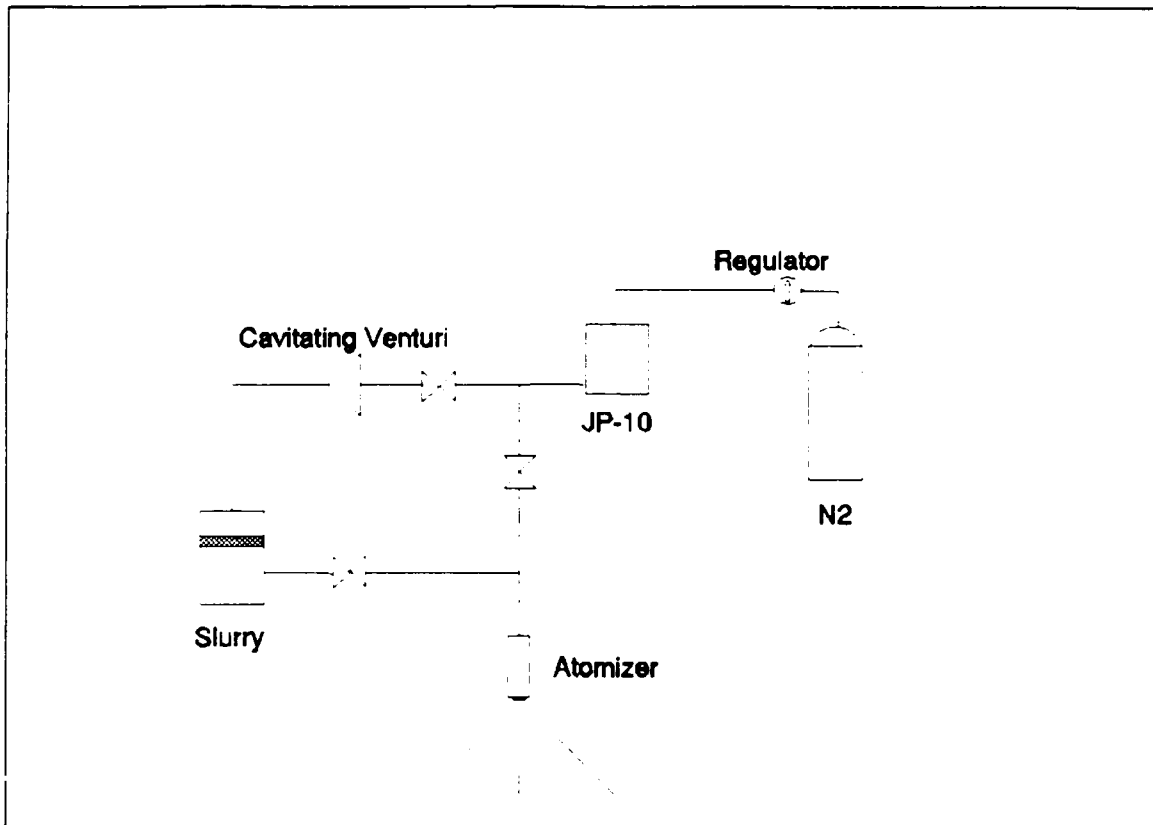


Figure 2: Fuel Delivery System

venturi to maintain a constant mass flow rate of JP-10. The cavitating venturi was previously calibrated to determine the mass flow rate of JP-10 for varying nitrogen pressures. The JP-10 pressurized the top of a piston in a tank containing the gelled slurry fuel. The slurry was then piped to the atomizer. A by-pass line allowed for purging the nozzle with JP-10 after each run. Fuel mass flow rate is calculated by assuming the JP-10 and slurry to be incompressible and equating their volume flow rates.

The air delivery and ignition system shown in Figure 3 can deliver up to approximately two lb_m/s of air at a temperature of about 1250 °R. Air was supplied by a bank of high pressure tanks. Pressure to the motor was regulated by a pneumatic dome loader. Before entering the combustor the air was heated using a hydrogen-fueled air heater. The air was then split into combustion air and atomizing air. Air mass flow rates were varied by changing the sizes of sonic chokes located in the different lines. Ignition of the air

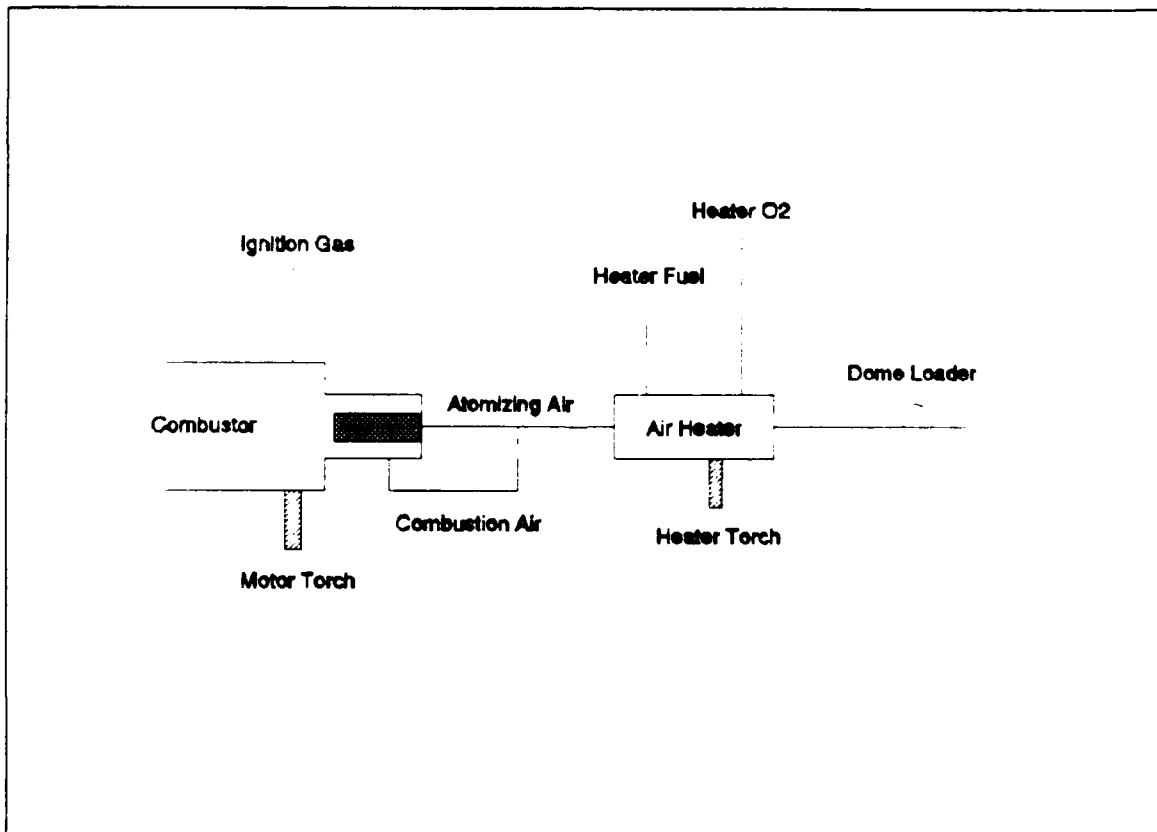


Figure 3: Air Delivery System

heater and of the combustor was achieved by the use of spark ignited torches that were fueled by ethylene and oxygen. Ignition in the combustor was also assisted by the injection of hydrogen into the recirculation region of the sudden-expansion inlet.

The sub-scale ramjet combustor designed for this study was a single-step, subsonic, sudden expansion "dump" combustor. Flow to the combustor expanded from a diameter of 1.5 inches to a diameter of 3.25 inches (0.875 inch step height). A recirculation zone downstream of the step acted as a flameholder to provide flame stability. The combustor was designed for axial fuel injection. The atomizer body was located in the center of the inlet air flow. The position of axial injection could be varied in order to find the optimal injection location for sufficient fuel penetration into the recirculation zone for adequate flame stability. At the head-end of the air inlet air was injected through two, 180° opposed jets. This created swirling air in the annular flow surrounding the centrally located atomizer body. The length of the combustor was 20 inches from the dump plane to the exit nozzle, providing approximately 60 milliseconds of residence time. Two exhaust nozzles were used. One was sized ($d=1.45$ in.) for a mass flow rate of $1.05 \text{ lb}_m/\text{s}$ and a chamber pressure of $75 \text{ lbs}/\text{in}^2$. The other was sized ($d=1.0$ in.) for a mass flow rate of $0.50 \text{ lb}_m/\text{s}$ and a pressure of $90 \text{ lb}/\text{in}^2$. For

combustion efficiency calculation, static pressure taps were located just upstream of the exhaust nozzle.

The fuel used for this experiment was a gelled metalized slurry of JP-10 and solid boron carbide particles. The slurry, provided by the Naval Air Warfare Center, Weapons Division, China Lake, California, consisted of 50% boron carbide (B_4C) by mass, 38% JP-10, a small amount of magnesium, a catalyst and a gelling agent. The boron carbide particles had a Sauter mean diameter of nine microns. The slurry was dark gray to black in color. At ambient temperature, the slurry was highly viscous and would not pour. It had to be scooped into the fuel tank.

B. EXPERIMENTAL PROCEDURES

1. Atomizer Spray Characterization

The particle size distributions produced by the airblast and ultrasonic atomizers were measured using the Malvern 2600. Measurements were taken in a non-reacting flow spraying into ambient conditions. The experimental configuration for these measurements is shown in Figure 4. Measurements for the airblast atomizer were taken at varied axial positions for a fixed air/fuel ratio and at a fixed axial distance of two inches from the nozzle tip using various air/fuel ratios.

The ultrasonic atomizer presented a bit of difficulty in obtaining particle size data due to a combination of a very

wide spray angle and slurry particles deflecting off of the resonator cap at nearly 90 degrees, coating the cover glass used for protecting the Malvern range lens and the laser head. In order to protect the cover glass, aluminum plates, each drilled with a hole to allow laser light to pass, were inserted between the atomizer and the glass. Additionally, the position of the atomizer had to be carefully set so that, in combination with the aluminum plates, no spray would land on the cover glass during a measurement run. Spray droplets on the cover glass would have the effect of biasing the particle sizes measured in the spray, most likely to the large side. The atomizer position that gave no spray accumulation on the cover glass resulted in measurements being taken 0.25 inches from the tip of the resonator cap of the injector and one inch below the centerline axis of the atomizer. Measurements were taken with different fuel mass flow rates and air mass flow rates to determine the sensitivity of the particle size produced by the atomizer to these two parameters.

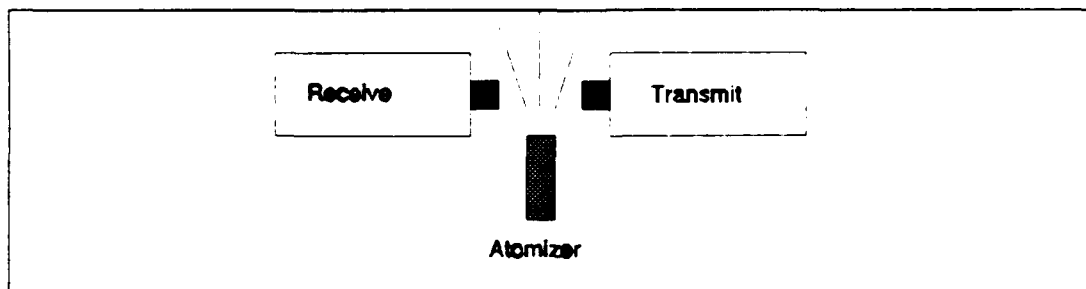


Figure 4: Configuration for Taking Particle Size Measurements Using Malvern 2600

2. Slurry Combustion in Ramjet Combustor

Figure 5 shows the subscale ramjet combustor mounted on the thrust stand. The combustor was initially assembled with the Delavan airblast atomizer installed. Many runs were made in order to find the optimal set of conditions that would result in ignition and sustained combustion of the slurry fuel. The airblast atomizer was then removed and the ultrasonic atomizer installed in its place. The motor was then fired under the same conditions in order to compare the performance of the two different atomizers in terms of combustion efficiencies achieved.

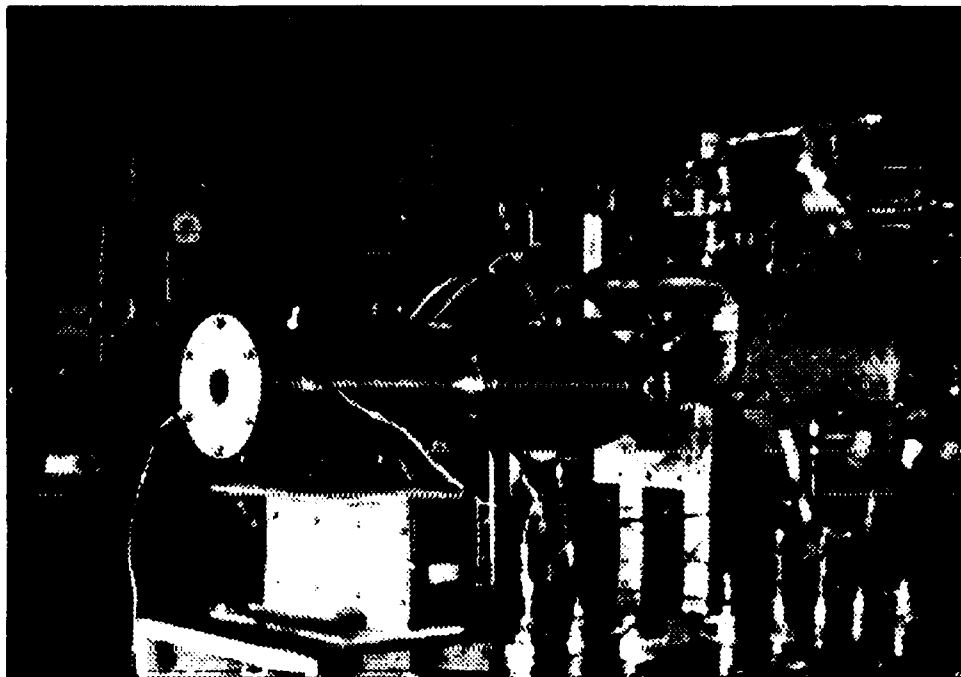


Figure 5: Ramjet Combustor

III. RESULTS

A. ATOMIZER PERFORMANCE IN NON-REACTING FLOW

1. Delavan Airblast Atomizer

The first set of particle size data taken on the Delavan atomizer was obtained using a fixed air/fuel ratio of six with varied axial positions. These parameters were selected in order to provide a basis for correlation between the current experiment and Guglielmi's results. An air/fuel ratio of six was the lowest ratio reported by Guglielmi. Figure 6 shows a plot of D_{32} versus axial position from the atomizer tip. Measurements taken at positions less than 2.25 inches from the atomizer tip resulted in a drastic increase in particle size. This was presumably due to the spray not being fully developed inside that distance. Beyond 3.75 inches, the obscuration measured by the Malvern was too low (too low a number density of particles) to consider the results reliable. In addition to considering the air/fuel ratio, it is important to note that the pressure drop across the atomizer required to generate this spray was 470 psig. The results shown in Figure 6 correlated very well Guglielmi's results at the same air/fuel ratio.

The next step with the Delavan atomizer was to collect data at much lower air/fuel ratios (and pressures) to observe

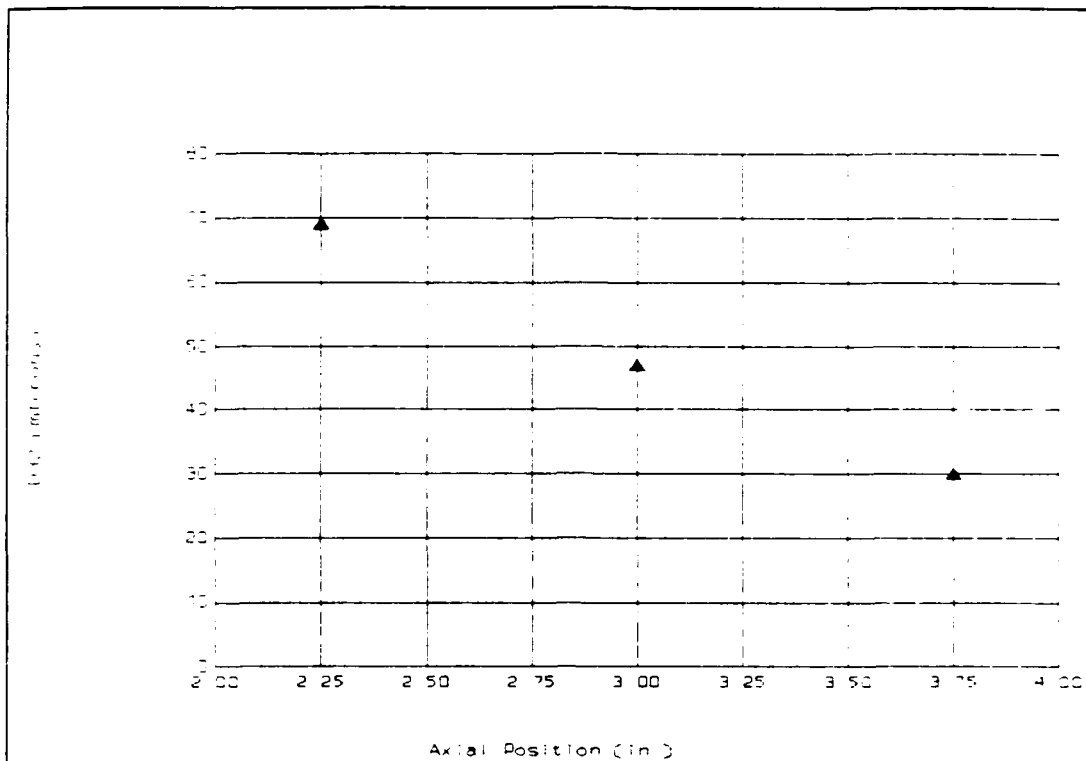


Figure 6: D_{32} VS. Axial Position Using Delavan Atomizer With MDOT A/MDOT F = 6

the performance of the Delavan atomizer at conditions closer to what is required for a ramjet application. In a ramjet application, pressures can be expected to be less than 200 psi and the maximum atomizing air/fuel ratio would typically be 0.1. Figure 7 shows D_{32} versus air/fuel ratio for air/fuel ratios between 0.17 and 0.77. For air/fuel ratios between 0.35 and 0.77, the nozzle produced a fairly regular spray with particle sizes around 75 microns. At air/fuel ratios less than 0.30, however, particle sizes increased drastically. Below a ratio of 0.17, the spray was sputtering and irregular.

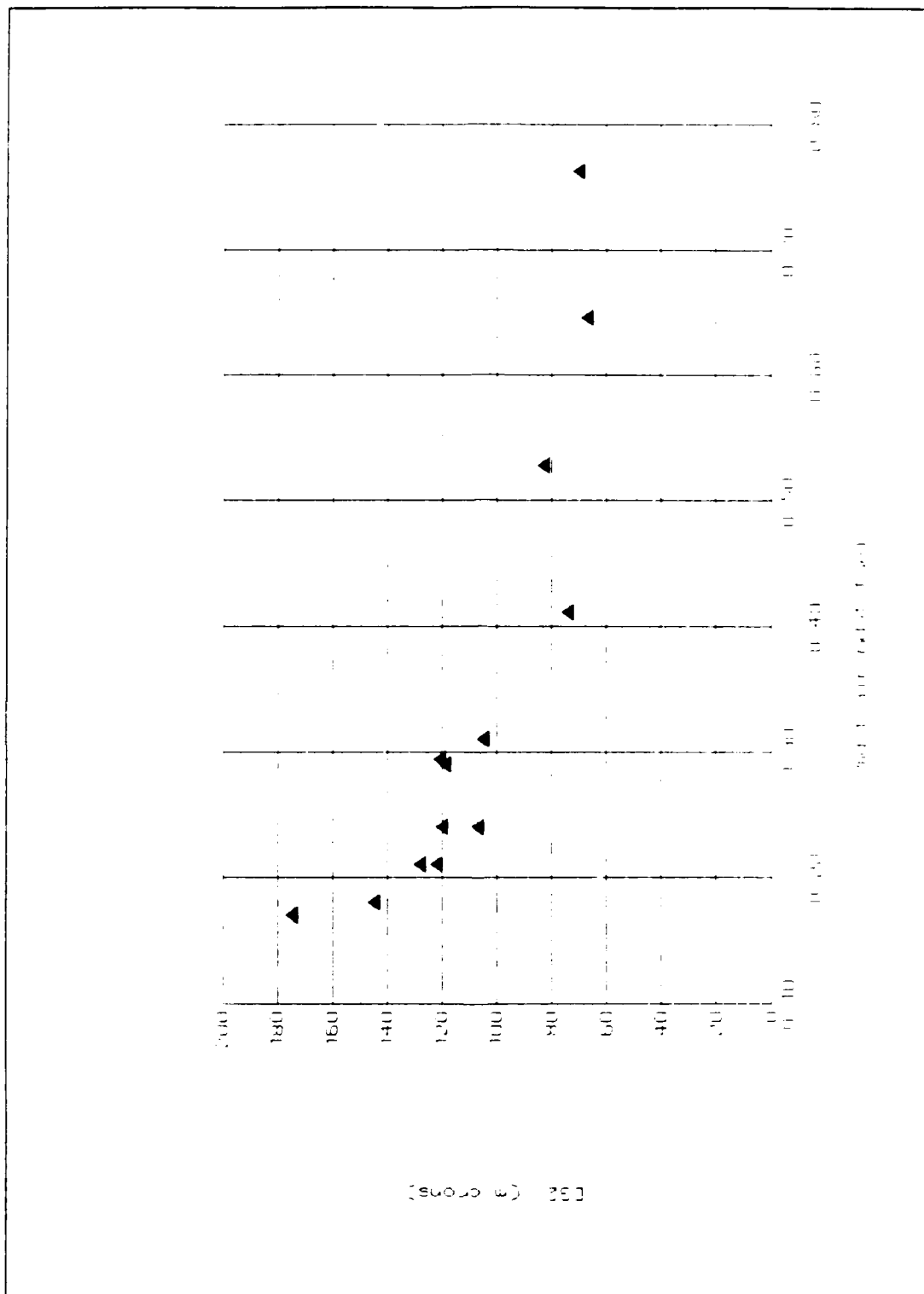


Figure 7: D_{32} VS. a/f Using Delavan Airblast Atomizer With MDOT Fuel = $0.035 \text{ lb}_m/\text{s}$

2. Ultrasonic Atomizer

Since the ultrasonic atomizer requires a much lower pressure drop to operate than the airblast atomizer, emphasis for this part of the study was shifted away from measuring the atomizer's performance with air/fuel ratio. Instead, particle size measurements were taken over a range of fuel mass flow rates of interest for two different air mass flow rates. The resonator cap on the ultrasonic atomizer used for this experiment was sized for a frequency within human audible limits. When operated, the atomizer emitted a very intense and high pitched whine.

Figure 8 is a plot of Sauter mean diameter versus fuel mass flow rate with an air mass flow rate of $0.217 \text{ lb}_m/\text{s}$. At the lower end of the fuel mass flow rate scale, values of D_{32} were measured as small as 40 microns. However, particle sizes steadily increased with increasing fuel flow rate. The atomizing air pressure used for this set of measurements was 150 psi, well within typical ramjet operating conditions.

The next set of measurements taken using the ultrasonic atomizer were at an air mass flow of $0.289 \text{ lb}_m/\text{s}$, using an atomizing air pressure of 200 psi, still reasonable for a ramjet. The results of these measurements are plotted in figure 9. This plot shows the same trend of increasing particle size with increasing fuel mass flow rate. If 40 micron particle sizes are considered to be acceptable, then

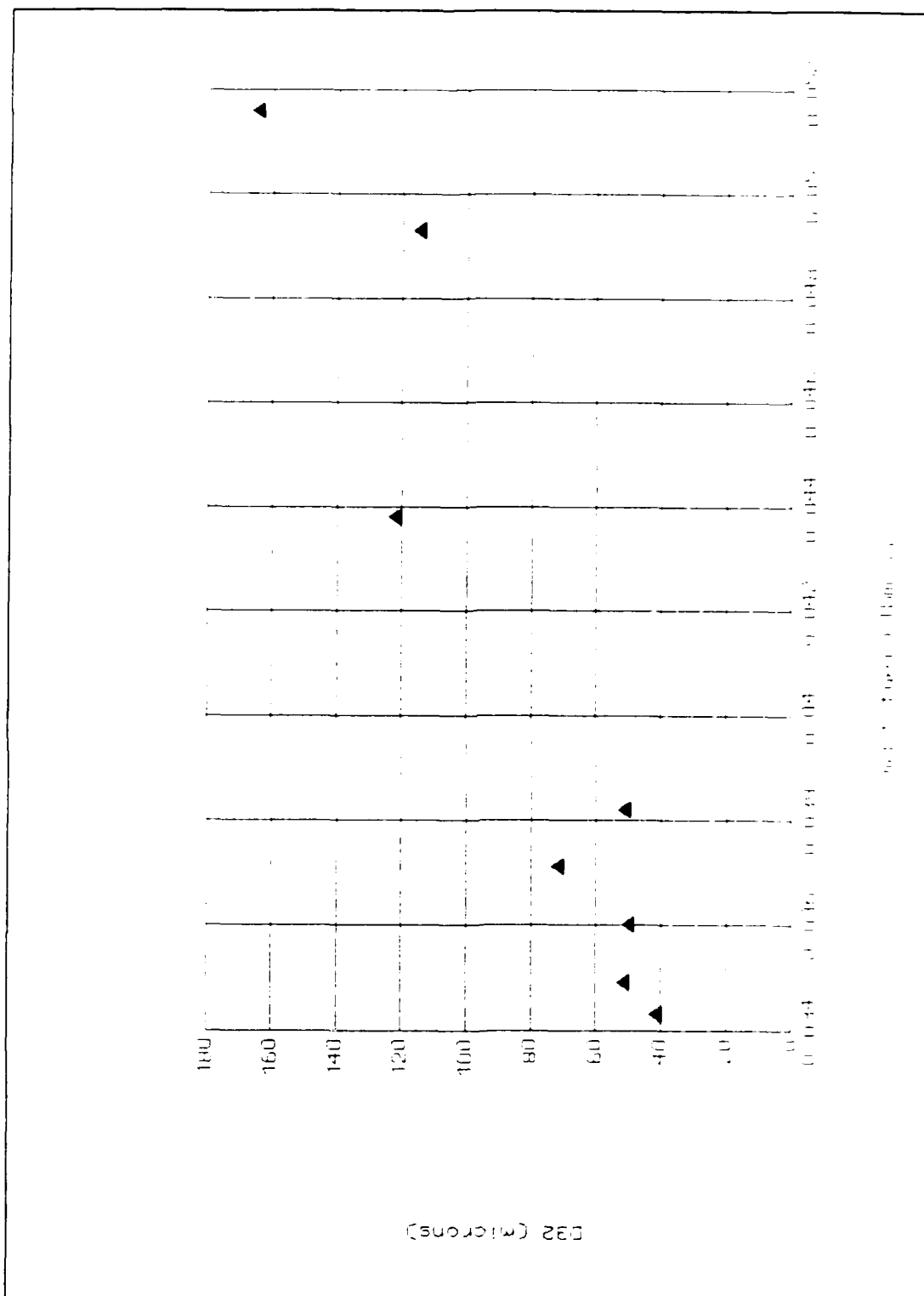


Figure 8: Particle Size VS. Fuel Mass Flow Rate, Ultrasonic Atomizer, MDOT Air = 0.217 lbm/s

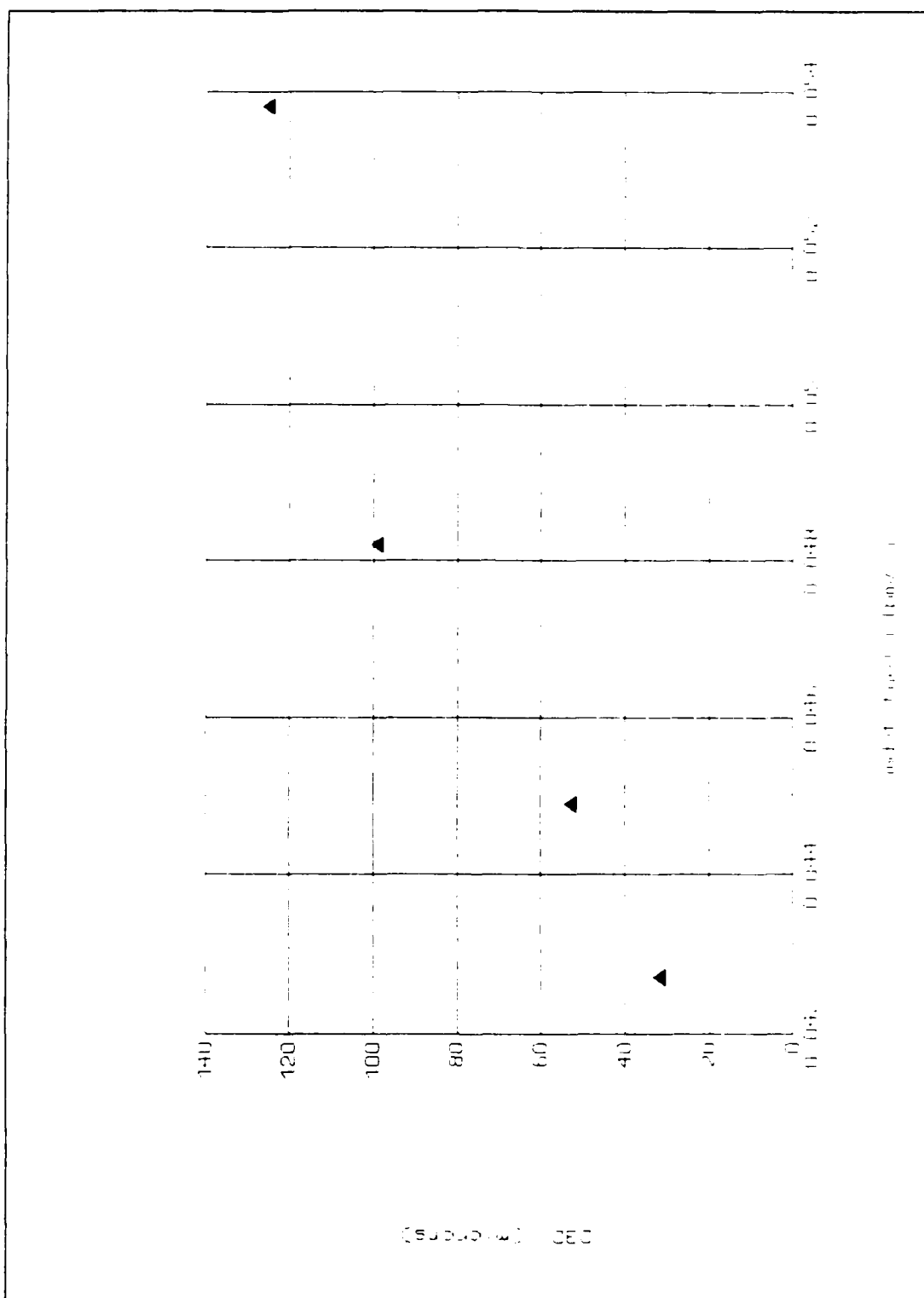


Figure 9: Particle Size VS. Fuel Mass Flow Rate, Ultrasonic Atomizer, MDOT Air = 0.289 lb_m/s

this higher air mass flow rate extends the range of useable fuel mass flow rates up to approximately 0.044 lb_m/s, compared to approximately 0.035 lb_m/s at the lower air flow rate.

B. ATOMIZER PERFORMANCE IN REACTING FLOW

1. Delavan Airblast Atomizer

In an attempt to find conditions resulting in ignition and sustained combustion of the slurry fuel in the subscale ramjet combustor, fifteen runs were completed. Parameters that were varied included the following: total air mass flow rate, atomizing air/fuel ratio, length of time that ignition hydrogen was left on, and the amount of JP-10 introduced into the combustor prior to the slurry fuel. The atomizing spray cone was located 0.25 in. downstream of the inlet dump plane. It was observed that ignition hydrogen alone provided insufficient energy to ignite the slurry fuel. Therefore, prior to each run, the fuel line feeding the atomizer was filled with JP-10. The JP-10 ignited readily and sustained stable combustion as long as the ignition hydrogen was left on. The conditions under which ignition of the slurry fuel was achieved were as follows: total air mass flow rate, 0.51 lb_m/s; fuel mass flow rate, 0.0396 lb_m/s; atomizing air/fuel ratio, 0.48, overall fuel/air ratio, 0.077 (equivalence ratio, 0.78). When the slurry fuel entered the combustor, combustion continued, but was audibly weaker than with pure JP-10 and sounded very irregular. When pure JP-10 was burning, the

chamber pressure peaked at 90 psia. Once the slurry fuel entered the combustor, the pressure began dropping off and started oscillating. The combustion that occurred was so irregular that a combustion efficiency was not reasonably calculable. Apparently, the momentum of the atomizing spray was insufficient to penetrate the swirling annular air flow and/or the atomization produced particles too large for rapid vaporization within the flame stabilization region.

2. Ultrasonic Atomizer

The ultrasonic atomizer was installed in the combustor and run under the same conditions that gave the best results with the airblast atomizer in order to make a direct comparison in performance of the two atomizers. The resonator cap was located 1.0 inch downstream of the inlet dump plane so that the spray cone would be located approximately at the dump plane. Due to the relatively large throat size of the ultrasonic atomizer, the atomizing air/fuel ratio was 4.44 (as compared to 0.48 for the airblast atomizer). As before, the run was commenced with pure JP-10 in the fuel line to generate sufficient energy in the recirculation zone to ignite the slurry fuel. When the slurry fuel reached the combustor, there was a marked difference both visually and audibly in the combustion as compared to the airblast atomizer. Furthermore, the chamber pressure sustained 96.0 psia over the length of the run. Strong and stable combustion of the slurry fuel was

achieved using the ultrasonic atomizer. The temperature rise combustion efficiency was calculated using the following equation:

$$\eta_{\Delta T} = \frac{T_{t4exp} - T_{tair}}{T_{t4th} - T_{tair}}$$

where: T_{t4exp} is calculated from the continuity equation applied at the nozzle inlet

T_{t4th} is calculated assuming equilibrium adiabatic combustion at the measured chamber pressure

T_{tair} is the inlet air stagnation temperature

Due to time restraints no attempt was made to optimize combustion efficiency or to determine the effect of equivalence ratio. In addition, the hydrogen ignition gas was maintained during this initial test (since it was required using the airblast atomizer). T_{tair} was, therefore, calculated assuming equilibrium adiabatic combustion of the hydrogen. In this manner the combustion efficiency of the gelled fuel alone could be estimated. The combustion efficiency achieved using the ultrasonic atomizer was 76 % at an overall equivalence ratio of 0.78.

IV. CONCLUSIONS

Both atomizers tested produced slurry particle sizes in the range necessary to achieve good combustion efficiency. The airblast atomizer required a large atomizing air/fuel ratio at the price of a large pressure drop, reducing the feasibility of using this atomizer in a slurry fueled ramjet. Since pressures above 200 psi are not readily available in a ramjet, atomizing air for the airblast atomizer would have to be turbo-pumped to the required pressure. This would greatly add to the complexity of the ramjet and, therefore, would not be a desirable feature. The ultrasonic atomizer used an even larger atomizing air/fuel ratio, but operated effectively at a much lower pressure drop across the atomizer due to the larger orifice size, making this a possible option in a slurry fueled ramjet. The ultrasonic atomizer also appeared to be less susceptible to clogging by the highly viscous particle laden slurry due to its large orifices.

In testing the atomizers under reacting flow conditions, the airblast atomizer failed to sustain steady combustion of the slurry fuel. Under the same conditions, the ultrasonic atomizer provided sustained stable combustion and yielded a combustion efficiency of 76% at a pressure of 96 psia and an equivalence ratio of 0.78. Under the conditions tested, the ultrasonic atomizer provided better atomization and,

therefore, better combustion. Another possible explanation for the difference in performance may be that the ultrasonic atomizer, with its much wider spray cone, provided better fuel penetration into the recirculation zone of the combustor than did the airblast atomizer. To test this idea, further investigation could include adapting the combustor for radial fuel injection directly into the recirculation zone. The combustor design incorporated the possibility for radial injection. It also will permit viewing windows to be installed so that future testing can measure fuel penetration and particle size distributions at the head-end of the combustor. Now that successful combustion has been achieved with the ultrasonic atomizer, further investigations are required (without the use of sustained ignition gas) to optimize the location(s) of fuel injection, the strength of the inlet air swirl and the inlet dump area ratio.

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